Design and Development of a Temperature Measurement System to Monitor Subsurface Thermal Processes

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Design and Development of a Temperature Measurement System to Monitor Subsurface Thermal Processes

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Introduction

This paper is written in partial fulfillment of a Master of Science degree for the University of California, Berkeley. The focus of the project described in this paper is to develop a system which can quickly, efficiently and reliably monitor the temperatures in the soil during subsurface thermal remediation processes. Because knowledge of subsurface temperatures is a desirable geophysical parameter of several subsurface technologies, this project may be useful beyond its original intent. The primary purpose of this project is to monitor the progress of a process called dynamic stripping developed to remediate underground gasoline storage tanks that have leaked at Lawrence Livermore National Laboratory, California. The dynamic stripping remediation process includes alternating the use of steam injection into the soil and electrode heating of the soil in order to enhance and stimulate the removal of the contaminating organic compounds.

In order to properly asses the progress of a thermal remediation process and to decide what proceeding steps to take during the remediation process, it is necessary to characterize the thermal state of the subsurface on a real time basis. This requires that the time increment between thermal characterizations be at least equal to the time between significant changes in the subsurface thermal state. Several important design parameters are discussed which must be considered to achieve an acceptable monitoring speed.

The final system is designed to realize the necessary monitoring speed without sacrificing the other important parameters that it must meet. This paper highlights the significant steps encountered as this goal was worked toward. The final design features are then discussed, and the appendices give information necessary to use or make adjustments to certain aspects of the system.

A crucial aspect of the design is the response time of the temperature sensor. The temperature sensing probe uses an infrared sensing device which has been recently invented. The use of this as a downhole temperature sensing device is a unique application. It provides many advantages over other more conventional sensors used to obtain the temperatures downhole. The most important advantages are its response time, measurement repeatability, and limited effect on the well's thermal environment.

Because few people are available to regularly attend to the task of monitoring the soil temperatures, the system is designed to minimize the number of people required. In addition, the monitoring system is designed to minimize the number of steps necessary before a final display of the temperatures at the various monitoring wells can be obtained.

Project Overview

The remediation process at Lawrence Livermore National Laboratory, California is a demonstration of the dynamic stripping process supported by the Department of Energy. The demonstration is conducted at a location where underground gas storage tanks have leaked between the 1960's and the 1970's. The plume from the leaks has migrated beneath the existing water table as a result of varying annual rainfalls. The deepest contaminated portions of soil were found 120 ft below the surface, and the water table at the beginning of the project is 95 ft below the surface. The extent of the plume is currently estimated to extend 500 ft in one direction and 400 ft in the other. The region with contaminant concentrations greater than 100 ppm of total hydrocarbons is approximately 300 ft by 200 ft. Biodegradation of the lower concentration regions is evident at the plume boundary and in the vadose zone. There are at least two aquifers and two aquitards in the region's subsurface with varying degrees of continuity. Hydraulic gradients are small, so that plume migration is primarily diffusive.

The dynamic stripping process is initially designed to proceed in two steps. The first is to preheat the ground with electrical current for a period of several weeks to maximize the energy input to the soil and to maximize the initial contaminant removal. The second step involves a schedule of alternating the electrical heating process with the injection/extraction of steam approximately every 12 hours. The electrical heating is designed to enhance partitioning of the contaminants from the lower permeability zones to the higher permeability zones. It also aids in the equilibration rate of the contaminants between the liquid and solid phases. The steam injection process takes advantage of the beneficial changes that occur to many of the contaminants at increased temperatures and pushes the volatized contaminants along a condensation front from the injection source to the extraction point. It is expected that the entire cleanup process will take approximately four months after the site construction is completed.

Figure 1 shows the layout of the site. Three closely spaced extraction wells are surrounded by six injection wells. The spacing of the injection wells from one another is about 100 ft. The extraction wells are also used as electrodes to electrically heat the soil although other wells are used exclusively for this purpose. Soil temperatures are expected to reach 120 deg C in the steam zones and up to 50 deg C in the lower permeability zones where the steam does not penetrate.

Monitoring the progress of the remediation process is accomplished with two methods. One method uses the system developed with this project, and the other is through the use of electrical resistance tomography (ERT). A complete characterization of the temperature profile at the monitoring wells makes it is possible to establish where the steam zones are near the monitoring wells and when they reach the wells, but temperature information between the wells must be inferred through some prediction scheme. The use of ERT helps to better define the temperature field between monitoring wells. This method essentially measures the electrical resistivity between any two points in any two wells, and an analytical procedure determines the resistivity field in the plane between any two ERT wells. It has been found that there is a correlation between electrical resistivity changes and temperature as well as the presence of steam. The ERT data is calibrated and supported by the more accurate temperature profile at the monitoring wells provided by the monitoring system developed in this project.

Four thermocouples mounted are to the outside of each well at depths of 80, 100 120 and 140 ft with the wires brought to the surface. This allows for a check of the monitoring systems accuracy and continuous monitoring even when the ground is being heated (downhole logging will not be permitted during electrical ground heating operations).

A total of twelve monitoring wells are emplaced at the LLNL site. There are six positioned to surround the extraction wells inside the region formed by the injection wells as shown in Figure 1. The other six are outside this area. Each well is composed of a fiberglass epoxy composite material 1/8 in thick. Their inside diameter is 2 1/8 in and they are 160 ft long. Each well is water sealed at the bottom and is expected to remain air filled except for condensation and small amounts of surface rain which will flow to the bottom. The well is created from 5 ft sections that are joined by internal threaded connectors which cause the well to have an inside diameter of 2 in at these points.

Since several aspects of the clean up procedure are new and experimental, a test was conducted at a nearby location which was uncontaminated. This was done prior to implementing the remediation of the contaminated site to verify the basic procedure and fine tune the process. The location of this test will be referred to in following sections as the **clean** site. The test utilized a single steam injection and extraction well and several monitoring wells at depths similar to the contaminated site. During the clean site test, efforts were made to measure the monitoring well temperatures. Although temperature data was gained that was useful, the device and methodology used to measure the monitoring well temperatures proved to be time consuming and was potentially difficult to apply to a larger scale situation.

Objectives of the Temperature Monitoring System

The ideal temperature monitoring system for a thermal remediation process would be one that could quickly and easily measure the entire temperature field in the ground at any time. There is no known method of obtaining this goal, but all current methods necessitate drilling wells into the ground. Under certain circumstances, the ERT method temperature data can be used to deduce the temperatures in the plane between wells, and from this data the entire temperature field can be inferred. The only accurate subsurface temperature data that can currently be attained are those at the well itself, and the temperature field is generally inferred from this data using a geostatistic model. Given these limitations, the development of an ideal temperature monitoring system strives to optimize the reliability, efficiency and cost of a system to measure temperature at any depth in a well.

The maximum time available to measure the temperatures in all of the wells depends on the time scale of significant subsurface temperature changes. For the dynamic stripping process that this monitoring system is designed, the progression of the steam through the soil creates the most rapid thermal changes. Laboratory experiments, the clean site test, and computer simulations performed using the contaminated site soil properties indicate that the steam will travel at an approximate rate of .1 to .5 ft/hr [Ref 1]. The variation in steam growth rate is dominated by the soil properties, the water saturation and the effect of geometric spreading. Thus, to approximate the position of the steam front it is necessary to obtain the temperatures in the wells at least once a day.

The cost of currently available downhole temperature measurement measuring tools is on the order of $20,000-$30,000. Twelve of these devices would be required if one wanted to measure the temperature versus depth in each well simultaneously without moving from one well to another. Not including supporting equipment (such as computer hardware and software), the cost would be over $200,000 for this particular project. The monitoring system developed has to cost significantly less than this to justify the necessary research and development and potential problems that could arise. Additionally, the budget limitations of this project precludes using any existing systems.

It is expected that no more than one or two people will be available for the day to day monitoring tasks and for maintenance of the equipment. This requires that the measurement devices must be easy to use and troubleshoot should problems occur. The process of system preparation, temperature measurement and logging, and presentation of the data needs to be simple enough that a single person could potentially perform all these tasks in a single work day. To prevent undue periods of down time, efforts should incorporate currently used and tested off-the-shelf components.

Because the wells are expensive to construct and logistically difficult or impossible to replace, the loss of even one because of an unforseen problem would be a significant setback. As a result, safety features must exist to prevent a catastrophic failure during the lowering or raising of the probe which might result in damage to the well. A certain degree of flexibility in the probe centralization is required to compensate for the existence of the joints every 5 ft and for any potential distortion of the well shape. The largest threat to well damage is the probe getting caught in the well.

Accurate temperature measurements are crucial to the system's success. The desired accuracy is such that global energy balance calculations could be calculated or that significant design changes could be reliably made based on the data. Since the expected temperature range is from 20 deg C to 125 deg C, a maximum desirable error would be 1 degree at the lower temperature and 5 degrees at the higher temperatures. Therefore, a nominal error of 5% would be acceptable.

Theoretical Considerations

Although potential problems may occur during the development of a temperature monitoring system which meets the design objectives, the most crucial element of the system is the temperature sensing probe. Past efforts have shown that the method which is used to measure the temperature can significantly effect the accuracy and speed of the measured value.

The number of acceptable sensing devices which achieve the desired objectives is primarily limited by the physical properties of the soil, device, well, and well fluid. The physical property which dominates the transient response time is thermal diffusivity. Both the soil and the fiberglass composite well material have very low thermal diffusivities primarily because of their low thermal conductivities. Thus, once a well surface has reached a steady state condition with the soil, it requires significant time to reequilibrate after a thermal disturbance. Any sensor durable enough to resist wear from well contact has been found to have minimum response times on the order of tens of seconds. The combined effect of the soil/well system and the sensor is a response time on the order of minutes. Because of the necessary measurement speed, a discrete temperature versus depth log would be required rather than logging as the probe moves continuously downward. The ideal measurement device would therefore be one that does not draw heat from the well surface.

Since direct contact with the soil is not possible, measurement of the well surface temperature is an approximation to the soil temperature on the other side of the well. Laboratory experiments have been conducted with heater tape wrapped around the well. These have shown that in the absence of significant amounts of natural convection, diffusion within the well results in an inside well temperature that is approximately 3 deg C lower than the outside well.

High temperature gradients in a direction parallel to the well do create a highly convective environment. This was exemplified with the well heated in the 110-125 deg C range in a localized region. During this experiment, temperatures between the inside and the outside of the well differed by as much as 9 deg C.

A study of convection in small diameter wells of infinite length [Ref 2,3] was done first by Hales and then Sammel. This analysis produce an equation which predicts the onset of convection

$$\beta = \frac{g\alpha\theta}{c_p} + \frac{C\nu D}{g\alpha a^4}$$

where β is the critical temperature gradient for the onset of convection, g is gravity, α is the volume coeficient of expansion [1/deg K], Θ is the absolute temperature, ν is the kinematic viscosity, and D is the thermal diffusivity. The well diameter is defined by a, and C is a variable which depends on the boundary coefficients and is 216 in c.g.s. units for an infinite well.

It predicts that in an air filled well of 2 1/8 in diameter the onset of convection will occur when temperature gradients are 5-20 deg C/m depending on the air temperature. Efforts were made to measure temperatures in the air space of a fiberglass well that had a copper pipe wrapped around it and was heated at a distance several feet below the measurement point as shown in Figure 2. Gradients in the range from 10±5 to 80±5 deg C/m were measured along the outside of the well. Various experiments were run where temperatures ranged between 50-125 deg C at the base of the well and 30-75 deg C in the instrumented portion of the well. This range of gradients was chosen to reflect the maximum expected gradients that would be seen in a subsurface steam zone as measured at the clean site [Ref 1]. Hot zones created using heater tape wrapped directly to the fiberglass well casing have predicted thermal gradients in the well of 10^4 to 10^5 deg C/m. It is not surprising that very large thermal gradients are experienced for this condition.

In all cases the air temperature in the well of the convection experiment was always below the temperature expected at the inside well surface. One indication that convection was present was that this was exhibited to a greater degree for the higher gradients. It was more evident that natural convection existed because of the random oscillation of the air temperatures with a time scale of oscillation on the order of one second. The amplitude of the oscillations also was greater for larger gradients and became as high as ±40% of the well temperature. Because of the uncertainty associated with the gradient calculations and the difficulty of achieving a uniform gradient, it is not clear that convection ever existed in the well when thermal gradients less than the predicted critical gradients prevailed. A more detailed study would be necessary to determine if the calculated critical thermal gradient for the onset of natural convection is an accurate prediction. The experiment did indicate that convection could be expected if one was to measure the air temperatures in the well rather than the surface temperature.

Radiation losses from the well to the probe are possible, but not likely to be significant. If the probe has a high absorbtivity and it is large enough to block a major portion of the field of view of the well from itself then enough energy could be absorbed by the probe to potentially distort the well temperature. For this to be an important concern the probe must also be stationary a sufficient amount of time for the effect to be significant.

The issue of thermal contact resistance is a concern for any method of measuring the well temperature through the use of a contact device. This is attributed to the surface roughness of the well and the surface characteristics of the temperature sensing device. An increase of pressure at the contact point should deform the high spots of contact and therefore increase the contact area between the two objects. This would in turn decrease the resistance to heat flow and result in an enhanced response time.

It is worthwhile to compare the advantages and disadvantages of temperature measurement in a water filled well or in a well composed of steel relative to the current configuration. Any device that measures the temperature in the fluid of a water filled well would have a faster response time because water has a thermal diffusivity two orders of magnitude greater than air. The enhanced ability of heat to conduct in a water filled well would also tend to smear the temperatures seen at the well surface. This effect might not be significant because if the water in the well is in static equilibrium with the water outside the well, similar conductive effects would exist on the other side of the well. The critical convection gradients in a water filled well are predicted to be much lower for any given temperature and well diameter so that one would expect greater convective smearing than in the air filled well. A steel well is more likely to provide fast response times for a contact measurement device since it would react much quicker to a small draw of heat from the sensor. The steel well would smear the temperatures along the well because of its high thermal conductivity. Some of these effects are evident in a paper by Griston [Ref 4]. So, even though the air-filled fiberglass well may provide a poor setting for quick temperature measurements, a device which draws very little energy from the well side may achieve the most accurate soil temperature versus depth data.

<u>Measurement Probes Considered</u>

A considerable amount of time was directed toward finding the probe which best met the design objectives of the project. Since many of the lessons learned may be useful for further efforts in the thermal characterization of subsurface environments, a brief discussion of the devices explored is given along with any points of interest.

The device used to measure monitoring well temperatures at the clean site was a thermocouple contact system [Ref 1]. Ten thermocouples of 24 gauge wire were mounted on a 1/2 in diameter hollow fiberglass support tube that could be broken down into sections. The thermocouples were placed at one foot intervals along the side of the tube as shown in Figure 3. Copper foil was attached to each thermocouple to increase the thermal contact with the well side, and each had a felt backing for thermal insulation from the tube. Opposite from the thermocouples, small tire inner tubes were attached to the support tube. Air pumped into them from a tube extended to the surface provided the necessary contact force.

This method was discontinued for use at the contaminated site even though it gave accurate temperature data. The time to equilibrate with the well was approximately half an hour. Lowering the device ten feet a time meant it took a full day to characterize an entire well for each probe. It may have been possible to automate the process with a computer controlled system but too many channels of data acquisition would have been required to characterize all the wells simultaneously. It also was not obvious that the system would reliably lower and raise by a motor driven mechanism.

In response to these problems, a probe was designed that used a single thermocouple sensor made of the two dissimilar metals, but instead of being made from wire, they were composed of metal strips .01 in thick, 1/8 in wide, and 1 in long. This thermocouple was bent to fit on a lever which was forced forward to contact the well surface by a small air piston. It was to have been activated and retracted by a computer actuated air valve attached to an air tank. Because there was only one temperature sensor the equilibration time needed to be significantly reduced. The response time was brought to within about three minutes which was nearly acceptable for discrete sampling at one foot intervals. A 150 ft deep well would have been logged on one foot intervals in 7 1/2 hr. There was still concern of the risk that it would be unreliable. In addition, there was a desire to have the potential for better resolution than one foot.

A new design was created to address the reliability issue as well as to decrease the response time. The primary concept used a very fine thermocouple wire between .001 in and .003 in. The response time of these thermocouples in still air ranged from 5 msec to 1 sec. This allowed for a lowering rate of 4 in/sec to achieve a resolution of less than 1 ft in depth if logging were to be done continuously. The thermocouple was attached to a centralizing tool with thermocouple extension wire and a wire strain relief passing through it. During the testing of this sensor, the issue of natural convection arose. It was expected that some convection would be seen in the steam zone areas. The degree of variation exhibited when heater tape was wrapped around a well section was greater than was hoped for. This is the reason the experiment was conducted to simulate a steam zone thermal gradient.

The steam zone simulation showed that the temperature variations were too great and randomly oscillatory to predict the temperatures of the soil in regions where convection was occurring in the well. In addition, it seemed that the thermocouples would probably break over short periods of time. Even though they are inexpensive and would have been relatively easy to replace, a regular maintenance item like this was not a preferable liability.

Final Probe Design

In spite of the deficiencies of the thermocouple probe, efforts were going to be made to compensate for the convection induced errors, and this was likely to be the final design. Other contact devices that were yet untested may have had potential. During the fine wire thermocouple testing period a new product was introduced to the consumer market that resulted in a new direction for the sensor design.

This product is called an IR t/c infrared thermocouple produced by Exergen Corporation. This device responds to infrared energy in a manner similar to a thermocouple since dissimilar metals are an integral part of the design. That is, the voltage potential measured at the output is a function of the infrared energy absorbed at sensor, the temperature at the output, and the material composition of the sensor's output wires. A semiconductor circuit gives an output proportional to the difference between the infrared radiation and the temperature of the output wires. Evidently, two different wire materials similar to a thermocouple are required to achieve this thermoelectric effect. This effect is produced with the use of a proprietary semiconductor technology which currently has a patent pending. The primary benefit of a device such as this is that the temperature of the well wall could be measured directly without contact. Because it functions like a thermocouple, it does not require power, and because it is self-contained it is relatively rugged.

There are several important features of the IR t/c which are directly related to the well measurement project. Since the device responds to absorbed infrared energy the element whose temperature is being measured must have a reasonably high emissivity. The device can be ordered to have standard dissimilar metal thermocouples as output wires (i.e. type T, K, J). The sensors simulate output voltages within a claimed 2% accuracy relative to the thermocouple wire counterparts over a relatively narrow and limited temperature range (50-90 deg C for the device chosen for this project). Because the repeatability is a stated $\pm$1% over a large range a calibration curve is possible. The sensor is 1.75 in long, .5 in in diameter and weighs .5 oz. It is rated to 100 deg C without cooling. The response time of the devices is claimed to be 80 msec, and the field of vision is 2:1 (the diameter of the target is double the distance of the target). The cost is currently just under $200 each.

Even though the sensor is rated to a maximum temperature of 100 deg C and the well temperatures may be as high as 125 deg C, the sensor is expected to endure these elevated temperatures for the short duration that they are to be encountered. Since the resolution is to be on the order of 1 in and the response time is on the order of .1 sec, the maximum speed of descent to maintain accuracy is about 1 ft/sec. The sensor is sensitive to dust collecting on its lens. Condensation of water on the lens is a potential problem.

The dimensions of the sensor relative to the well are such that it would be awkward to mount it perpendicular to the well, so it is necessary to mount it parallel to the well and reflect the infrared energy from the well surface to the sensor as shown in Figure 4. The reflector surface as well as the sensing end will have to be cleaned periodically to insure consistent calibration and accuracy. The resolution of this mounting method combined with the well diameter and the field of vision is about 2 in.

This sensor has been chosen as the sensor to measure the temperature in the wells because none of the limitations of the sensor represent potential design flaws. It is a benefit that fiberglass well material has a high emissivity, but because the exact emissivity may affect the device's sensitivity, and because the output is not identical to a thermocouple over the desired temperature range, a calibration using the well is required.

Measurement System Features

The choice of the proper temperature sensing device is the primary design concern for an acceptable measurement system. After this design goal had been achieved, other issues had to be resolved in order to meet the objectives of the project. A final schematic configuration of a monitoring device for a single well is shown in Figure 5.

Since the sensor behaves in a manner identical to a thermocouple, thermocouple wire is necessary for use as the extension wire. Because it is necessary to spool the wire at the surface when raising the probe, a stranded wire is required to prevent breakage and to allow greater flexibility. A 24 gage stranded wire was chosen because it is resistant to taking on a "set" when being wound, strong enough to support the 4 lb probe, and heavy enough to provide a quality signal transmission. A type T thermocouple was chosen because of its relatively low cost, high Seebeck coefficient and availability.

In order to measure the depth of the device as it travels down the well, the thermocouple wire is passed over a counter wheel which has a magnet attached to it. The counter wheel was used instead of the spool which the wire wraps around to insure a constant circumference. The magnet triggers a reed switch when it passes by. This in turn allows a 12 volt signal to pass to an input module monitored by a data acquisition system. The input modules are essentially optically isolated relays which trigger a TTL signal to the data acquisition system. A 100 ohm resistor is connected in series with the counting switch to prevent a possible unloaded short circuit to the power supply.

The data acquisition system has been configured to sum the number of times the counter wheel rotates, multiply the sum by its circumference, and add this to the calculated depth change in between full rotations. The last calculation is approximated by determining the velocity during the last rotation and multiplying this by the time elapsed since the magnet last passed the switch.

The data acquisition system was purchased from Strawberry Tree Inc. (San Jose, California). Ease of set up and use were the main reasons for this. The data acquisition system works well with an Apple Macintosh IIci chosen as the computer to receive, manipulate and present the data. The software designed to work with this data acquisition system is called Workbench Mac. Even though the software is not extremely versatile or robust, it is very easy to use, and it is able to accomplish all the tasks necessary for the project.

The heart of the mechanism which triggers the device to go down or up is two FPFT non-latching relays. Each is designed to be self-latching. As with any relay, a current passes through the coil to trigger the relay. The resulting switch closure allows current to pass to the motor. The relay utilizes another pole on the relay to allow current to continue to pass through the coil. Only once the flow of current to the coil is broken will the relay return to its non-triggered state where the motor will stop. Thus, the up and down switches are normally open while the off switches are normally closed. Three MOV (varistors) are used to prevent potential failures of the relay contacts due to welding on start up. A schematic of the electronics configuration for each device is shown in Figure 6.

The thermocouple passes through the inside of the spool and is attached to a low resistance, low noise, inexpensive mercury slip ring supplied by Mercotac Inc. The other end of the slip ring is connected to a thermocouple transmitter which supplies a 4-20 mamp output linearized to a type T thermocouple between 0 and 150 deg C. This transmitter has a zero and span adjustment which allows for a linear calibration. The transmitter output current is passed through a precision 25 ohm resistor which is a standard value, and the voltage drop across this resistor is measured by the data acquisition system.

There is a lever switch mounted just above the counter wheel with the lever situated about 3/16 in above point the where the thermocouple wire passes. This lever switch is connected in series with the other off switches in the system. Two lead sinkers shaped like miniature "footballs" are trimmed and squeezed onto the cable; one is mounted a couple feet above the probe and the other is mounted about 150 ft from the probe. The first is designed to turn the logger off when the probe nears the top, and the second is to turn it off when the probe approaches the bottom of the well. As a sinker passes beneath the lever, the switch is triggered.

The cables used for switching each box on and off are connected to a remote switching box. The internal wiring of the switching box is shown in Figure 7. The switching box is designed to trigger some or all of the devices to run simultaneously from a remote location. It has been designed which is patterned after the three separate switches (up, down, off) present on each logger. In addition to these three switches on this main remote trigger box there is a separate DPDT switch connected in series to the up and down switches of each logger which can disable each box individually. The switching box which triggers all the loggers to travel up or down simultaneously could also act as a conduit for electrical communication from the separate up and down switches of each box. Diodes are connected to each channel at the switching box to prevent an event where triggering a logger at its location could trigger one at another location.

A standard 120 volt AC to 12 volt DC adapter is used as the power supply for the thermocouple transmitter. It also supplies the current to trigger both the input modules from the counting wheel and the relays. It is rated to 500 mamp which is more than adequate for the drain from the devices it powers. It was chosen primarily because of its low cost and because it allowed for a degree of redundancy. Should one fail, the other devices would not be effected, and each is easily replaced.

The rear wheel of a bicycle is used as the spool for the thermocouple wire. There are two reasons this choice was made. The first is that it comes as an integral unit including bearings, axle, drive gears, and "spool" requiring minimal modification, and it presented an economical alternative over a more standard winch spool design. It is fortunate that the drive gears use a standard roller chain pitch for which motor gears are readily accessible. The other reason the bicycle wheel was chosen is that the freewheel which drives the wheel is a pawl mechanism which allows for no torque transmission in one direction. This provides a safety feature which prevents the thermocouple wire from unwinding if the probe gets caught while traveling downward.

Although the freewheel prevents problems with a probe accidently getting stuck on the way down, a safety feature is added to prevent a problem while being raised. This is a potentially greater problem because if the probe gets hung while rising, the motor could provide enough torque to snap the thermocouple wire and possibly debilitate the monitoring well. To prevent this, an adjustable tension roller is mounted to the chain. This tension roller has an arm of adjustable length which is positioned so that when tension in the chain is greater than the tension on the roller, the arm moves upward into a roller lever switch. The switch is connected in series to the off switch. This effectively prevents undue tension in the thermocouple wire.

Because the chain, gears and wheel are all metal, electrical noise from the AC/DC motor is transmitted through the motor drive shaft up into the thermocouple wire. A plastic shim and keyway is constructed to fit between the motor shaft and drive gear. This provides the necessary electrical shielding from the motor.

Noise from the winding of the thermocouple wire occurs from what is attributed to a change in the inductance of the wire as it wraps around the wheel. Reduction of this requires the addition of a 100 μF capacitor across the thermocouple wire leads. This acts as a high frequency short across the leads. The magnitude of the capacitor is large enough to eliminate as much noise as possible without compromising the response time of the system. In addition, the wheel the wire is wrapped around is grounded. Although this noise problem did not exist in the lab, it seems that the effect occurs more prominently in the field. Future designs will incorporate a shielded lower gage wire.

A small amount of persistant signal noise is still present even when the motor and probe are not moving. The noise can be produced by plucking the thermocouple wire. During measurement operations, the noise low enough to be acceptable (generally less than .5 deg C), but its elimination is currently being worked on. Possible contributors are interaction with the earth's magnetic field or minute changes of capacitance in the wire when it vibrates.

In order to prevent power supply or motor noise invading the signal data, each device uses two separate wire cables. One to is used to send data and the other is to switch the motor on and off. A four pin microphone connector is used to send data, and a five pin connector is used for switching purposes even though only four of the pins are used. This is to prevent cross connecting the cables.

The cost objectives of this project were met. It costs approximately $1000 in parts and $1500 in labor to build each logger. Computer hardware and software as well as the development cost are not factored into this estimate.

Calibration of System

Calibration of the measurement probes is a somewhat time consuming but necessary task because the deviation from linearity of the sensor relative to a type T thermocouple is not negligible. The first step in the calibration procedure is insure a uniform output of the thermocouple transmitter. This is useful because assuming that the deviation from linearity is similar for different probes, the curve fit necessary to compensate for this should be close for different probes when the transmitter has a standardized output. The next step is to calibrate the probe while it is attached to the transmitter in a thermal environment that replicates the field conditions. Even though the final calibration may be off. The fixed thermocouples in the monitoring wells can be used to make any final adjustments.

To achieve a uniform transmitter output, a type T thermocouple wire and junction are connected directly to the transmitter, bypassing the probe, the probe wire and the slip ring. The thermocouple is introduced into an insulated ice bath first and then an insulated bath of rapidly boiling water. After applying the equation $y=9.375x-37.5$ (the linearization from 0-150 deg C for a 4-20 mamp output) to the transmitter output, the zero and span are adjusted to read .2 and 99.5 for the respective baths. This provides a two point calibration of the transmitter with the deviations from 0 and 100 accounting for deviations from pure water properties at least in the lab where the original calibrations have been conducted.

The next step is to characterize the response of the probe in a manner that reflects how it will respond in the well. It is still necessary to compensate for the non-linear deviation relative to a thermocouple and to insure that the probe will have an output which accurately reflects the well temperatures. To achieve this, a calibration method has been devised which simulates the thermal environment which the probe will encounter in the well. A schematic of the calibration fixture is shown in Figure 8. A section of well about 1 ft long is instrumented with several thermocouples. At least one should be mounted on the inside surface, and another should be on the outside of the well opposite from this one. Two thermocouples are a minimum requirement, but for an optimal calibration it is advisable to surround these two on the outside with as many as four other thermocouples mounted about 1" from the original two in different directions.

The thermocouples are then surrounded by a minimum 5 in section of copper pipe which is split in half along the pipe axis. It is held in place by a pipe clamp so that it is half above and below the inside thermocouple. Also held in place by the pipe clamp is a heater strip at least 3 in wide that just encompasses the outside of the copper pipe. The copper helps diffuse the heat to produce a more uniform thermal environment for the probe to measure; this is especially important considering the thermal properties of the well material being used. The entire section of well is surrounded by fiberglass pipe insulation to facilitate the heating process.

A worksheet on the Workbench Mac software program for the digital acquisition system is created for the calibration process. The thermocouples at the well section are monitored as well as the output of the probe through the thermocouple transmitter. The linearization equation for the transmitter is applied to the probe output. In addition to monitoring the current output value of the probe, the maximum output value is recorded over a several second time span. The reason for this is because if the calibration well segment has been properly constructed, the hottest portion of the well will be where the thermocouples are located, and when the probe is lowered past this point it will be easier to find the maximum probe output value.

The probe is first lowered into the well without any voltage applied to the heater tape. The probe output as well as the thermocouple temperatures are recorded. The heater tape is then charged with a voltage sufficient to raise the well temperature to about 35 deg C. It is important that the well section reaches thermal equilibrium, or else because the probe averages over the region it "sees", a non-uniform temperature field may be measured.

The probe is lowered into the well section with the center of the probe reflector pointed along the axis of the thermocouple inside the well section. Insure at this time, as well as for subsequent repetitions of this step, that the probe output is highest is when the probe reflector is centered over the inside thermocouple. If this is not the case, change the heater tape/copper pipe position to correct this problem.

The maximum probe output as well as the thermocouple temperatures are recorded. This is done for successive well section temperatures spaced between the temperatures of concern, namely ambient values and 125 deg C. Usually 4 or 5 data points is sufficient. After reaching the highest measured temperature, the procedure should be run while decreasing the temperatures. This will insure that the calibration represents a thermally equilibrated environment. A curve fit is derived from temperature versus probe output data through a least-squares fit process. This provides the compensation for the non-linear relationship relative to a thermocouple. It has been found that a parabolic fit is sufficient to provide the desired degree of accuracy, and a higher order polynomial would result in a degree of precision beyond the resolution of the current measurement method. The coefficients of the parabola are entered into Workbench Mac as an additional calculation to the transmitter linearization calculation.

Table 1 shows the parabolic coefficients for the probes used for this project. A couple of the earlier calibrated devices have parabolic curve-fit coefficients that are significantly different from the others. This is because the thermocouple transmitters were not properly adjusted prior to the probe calibration. Although this will not affect the accuracy of the device, a certain degree of uniformity has been sacrificed. This can always be rectified in the future by recalibrating these transmitters and then the probes. With these anomalies taken out, an average value for the coefficients is obtained as well as the standard deviation. If a temperature was calculated from any given nominal probe output value with these average coefficient values plus/minus the standard deviations, the resulting temperatures would vary by no more than 2 deg C. This is within the desired accuracy of the device. The importance of this is that if care is taken to adjust the transmitter properly, an acceptable degree of accuracy can be obtained without necessarily calibrating the probe immediately. It should be noted that it is much easier and less time consuming to perform the calibration on the transmitter than on the probe.

There was concern that the cold junction compensation on the thermocouple transmitter might effect the parabolic curve fit. That is, it was thought that data taken at an ambient temperature other than the ambient temperature at which the probe was calibrated might be inaccurate due to a constant offset (from the cold temperature compensation) applied through a non-linear parabolic equation. To test this, the transmitter and the thermocouple wire ends were enclosed in a box and uniformly heated to approximately 35 deg C. The result was that the deviation of the calculated temperature through the curve fit was noticeable, but not significant. The error was on the order of an average 3%. The calibrations were conducted at ambient temperatures between 20-25 deg C, and it is unlikely that ambient temperatures greater than 35 deg C will be encountered. It is expected that a similar effect with ambient temperatures down to 5 deg C will occur.

In addition to calibrating the probe, it is also necessary to perform a couple of calibration tasks to insure a proper depth calculation. The first is to measure the circumference of the counting wheel, and since the wheels are similar for all the devices, this is the incremental depth increase per rotation. The circumference of the encoder wheels used for this project is .573 m (1.88 ft). Finally, the initial constant depth offset must be measured for each device. When the probe is being raised it is automatically turned off when an ellipsoid shaped lead weight cinched onto the thermocouple wire passes underneath a lever switch. The location of this lead weight determines the final resting position of the device. Since the weight must once again pass beneath the switch on its way down, the device will stop when it begins its descent. It's descent is then restarted, and it is at this point that the depth calculations begin. Therefore, to input the depth above or below the surface at which the depth calculation is to begin, it is necessary to measure the depth the probe rests at once it's descent is initialized. The offset is input in the Workbench Mac program which is discussed in greater detail in the appendices.

Presentation of Data

When a set of wells is monitored, data is sent to an ASCII format text file which contains the temperature versus depth information for each well. This file through the use of various software programs, can be used to present either temperature versus depth plots for each monitoring well or a 3-D picture with temperature represented on a color or gray scale. Either process utilizes a macro programmed in Excel. This macro either directly creates the plots or manipulates the data so subsequent programs can produce the 3-D picture.

The program which creates the 3-D picture is called Dicer produced by a company named Spyglass. The Excel created file has the x and y coordinates as well as temperature and depth. A utility named Sparsefill, also produced by Spyglass, converts this file into a nxnxn matrix which fills in data points for the 3-D picture that are not given in the data. Values of zero are placed into the unknown locations with a matrix fill operation that plots only the project points. Sparsefill also provides for another more computationally intensive method of filling in the unknown data through the use of kriging, a geostatistical analysis procedure. The kriging analysis infers the temperatures in between monitoring wells. This may be helpful in locating steam zones.

Appendix 1 - Use of Excel Programs

Two macros (interactive semi-automatic operation performing programs) have been written using Excel 3.0 to reduce the temperature versus depth data to a presentable form. Although briefly discussed in the text, it may be helpful to have further details. Although this discussion will not substitute for a knowledge of Excel, someone with a background in Excel may find it easier to make changes in the macros if necessary. The macro spreadsheet has been named "LLNL data macro".

Both macros are begun with an object attached to them. That is, a button is placed on the screen and with the use of the "Attach to object command", a macro can be run by clicking the mouse on the button.

The first macro, the one on the left of the sheet, produces a four column data text file. This file is used by Sparsefill and subsequently by Dicer to present a 3-D picture of the temperature. The macro steps through the following commands:

• An input command queries the file where the original temperature versus depth data file is stored.

• Another input command queries the file location and name to store the Sparsefill formatted file.

• The original file is opened, and the last row of the file is located. This is necessary for subsequent cut and paste operations. This is done with the Get.document(10) command and is defined as "lastrow".

• Extraneous information like comments, time and date are removed.

• The temperature versus depth data from each well is cut and paste so that when this step is completed there are two columns, depth in the first and temperature in the second. The data for monitoring well #2 is located beneath that of #1, and #3 through #12 are beneath those in order. This is done through the use of a For-Next command (like a do loop). Multiples of "lastrow" increment the position of the cut and paste commands.

• Two columns are inserted to the left of the existing two columns, and the x and y coordinates are placed in these for each well. These coordinates are copied and pasted from the macro sheet where they may be entered.

• This created file is saved according to the desired file name and Excel quits.

For day to day progress reports rather than an overall picture of the operation, temperature versus depth plots may be more informative. The other macro to the right of the macro sheet creates temperature versus depth plots. Each plot may have as many wells plotted on it as desired. The data file created from Workbench Mac is used as the data file for the plots.

• The original file is opened, and the last row of the file is located. This is necessary for subsequent cut and paste operations. This is done with the Get.document(10) command and is defined as "lastrowb".

• An input command requests the maximum scale desired on the graphs. A set of input commands requests what plot number each well should be graphed on.

• A For-Next loop begins. Each time a loop occurs one plot is created. The increment of each loop is named "graphnumber".

• A scatter plot is created with the desired layout. The Edit.series command defines a new set of data for a single line on the graph. The first line of the plot is located from the input commands as the first well with the same value as "graphnumber". This well is defined as "first series".

• A new loop begins that creates the rest of the plots on the graph. Each new series uses an Edit.series command.

Appendix 2 - Use of Dicer and Sparsefill

Sparsefill and Dicer (both created by Spyglass, Inc.) are necessary parts of the 3-D picture creation process. The first step is to apply the Excel macro discussed above, followed by an application of the Sparsefill utility, and finally Dicer is used.

At the present time a simple macro-like procedure of obtaining a 3-D picture has not been produced. It is likely that in the future, a software program will be available which will provide the option for someone with no experience with Sparsefill or Dicer to produce a 3-D picture. It may already be available but has not yet been identified.

Once the Excel data file has been created, Sparsefill is run by double-clicking on the application icon in the Spyglass utilities folder. The following steps are taken to create a file useable by Dicer:

• Choose "Process new data". After choosing the file created by Excel, a few seconds will pass, and then a dialog box will appear. It should state that no comment lines or header lines are in this file in addition to having four columns. The number of data points from all the wells will be indicated. Select "Ok" to this information.

• A dialog box will appear with several items of information which will need to be adjusted. The minimum and maximum variable range at the top of the dialog box are the temperatures measured in the ground. Alter the minimum to be several degrees less than the default value. This allows wells to be more easily located when using Dicer. It is possible that there are wells which were not logged, and they will have very small or negative values. In this case, put a lower bound on the expected minimum (say 10, which is less than the expected lowest temperature value).

Expand the first two dimensions from the top to have a slightly smaller minimum and a slightly larger maximum than the default values. This insures all the wells will not be on edge of the 3-D space.

• It is sufficient to represent the wells in the x-y direction with blocks of several feet. In the z-direction, however, an increment of at least one foot is preferable. Storing the data with the x,y increments having a larger size than the z-direction will conserve a considerable amount of storage memory. The best way to achieve this and still produce a picture which is scaled properly is to give the x and y coordinate increments a reasonable value, say 1.2 m, and then to give the z-increment the desired increment which is some multiple available in the zoom feature of Dicer. The value which seems to work best for this project is .3 m; a four times zoom is available in Dicer.

• Before choosing "Ok", make sure that "Project points only" is chosen. One will probably never want to choose "Simple matrix fill" as this will not provide any useful added information to the data. "Kriging" may be chosen but will be discussed shortly. Using "Project points only" will give a picture of the well data, leaving all other points at the minimum value.

• Save the file as desired.

If one desires to try and interpret the temperature field in between monitoring wells, a geostatistical analysis called kriging is provided in Sparsefill. To implement this procedure, choose the "Kriging" option rather than the "Project points only" option. In addition to completing the previous steps in Sparsefill, the following step must be performed:

• Once the "Kriging" option is chosen, a "Kriging settings" selection becomes available. Selecting this provides a menu of adjustable values which govern the kriging analysis. Most of the default values are acceptable, but it has been found that are certain values which can be changed to minimize the amount of computational time and optimize the resolution of the picture. For the data field expected to be seen with this project, the maximum sample size should be 40, and the minimum block size should be 4. For the 3-D space of concern, the matrix filling operation will take about four hours.

After creating a data file in Sparsefill, Dicer is activated. A discussion of how to view the well data will be provided first, and this will be proceeded by directions to view the kriged 3-D picture. The preliminary steps for both types pictures are addressed now. The file of concern is opened from the File menu. A dialog box will appear which allows for adjusting the picture scaling. In the "Data Range" section, select "Survey", wait a few seconds for the event to occur and then choose "Use Survey". Using the mouse, select the up-arrow for Dim0 (x-coord.), Dim1 (y-coord.), and Dim2 (z-coord.) under the "Target-Zoom" column. Adjust the Dim0 and Dim1 zoom values to 8 and Dim2 to 2. This 4:1 ratio is because of the 1/4 times zoom used in Sparsefill. Other 4:1 ratios may be chosen which will provide a larger or smaller picture on the screen. The 8:2 ratio is the largest which shows all the wells on the 21 in screen. Choose the "Nearest neighbor" interpolation method selection because the data appears less smeared. A picture of a blank box in space will appear after selecting "Ok" to the input values.

After a picture is created using either set of the following directions, the user may want to save the picture. To see this picture again in the future choose "Save Image Command" in the File menu. To play with this picture in the future choose "Save Configuration As" in the File menu. If the sparsefill data file name is changed or relocated, then Dicer will ask where the file is. This can be used to one's advantage if a new data file would require the same configuration as one created previously. Rather than stepping through the commands listed below, one merely has to change the name of the previous file, and when the configuration file is activated, the program will request where the data file is. The response to this would be to direct the program to the new data file. Configuration files are generally saved with a default name that ends with a negative number.

To view the well data:

• To locate the wells in the blank box, choose the Bottom Slice icon (3rd icon from the left). A knife tool can then be directed with the mouse. Mark a location somewhere in the middle of the box in space. All 12 wells logged into the dataset will appear on the slice with a color different from the background color.

• Choose "Automatic update" in the Special menu to make the check mark next to it disappear. This will prevent the program from redrawing every time a new slice is chosen.

• Select either the Facing Slice icon or the Side Slice icon (4th and 5th icons from the left). Position the knife tool over a box representing a well and press and release the mouse. Do this for any other wells shown on the horizontal slice.

• Choose "Orient..." in the Special menu. Press the "-" box next to the Dim 0 box. This will cause the surface of the ground to appear at the top. Press "Do Change".

• Select the transparency icon (2nd from the right) and use the tool to click somewhere on the background color of the horizontal slice. Choose "Transparency" in the Paint menu. This should put a check mark by this command. If it is already there, leave it alone. These steps will get rid of areas where no wells exist.

• Select the Tongs icon, and with the tongs tool, click on the side of the horizontal slice. Press the delete key (because this slice was just needed to locate the wells).

• Choose "Update now" from the Special menu. In time, the picture will appear. An important point is that the x,y,z and temperature data corresponding to the tool location is shown in the lower left corner of the screen. The x,y,z data gets shifted to have all positive values, so if there are negative x,y coordinates in the data, the most negative value will be at the zero coordinate values. Additionally, the well data will only accurately reflect temperatures proportionately. The values shown in the lower left corner indicate relative temperatures, not absolute temperatures. This is a bug in the program. Thus, the primary benefit of viewing this data is that it can be done quickly, and the "hot spots" can be seen. The data values are properly represented in the kriged data.

To view a picture of the kriged data:

• Choose "Automatic update" in the Special menu.

• Choose "Orient..." in the Special menu. Press the "-" box next to the Dim 0 box. This will cause the surface of the ground to appear at the top. Press "Do Change".

• If there are any regions of particular concern these may be presented by choosing a slice icon, selecting the slice of concern, and then choose "Update now" from the Special menu.

• The most simple way to view the data is to produce an animated sequence of the data. This is done by first choosing a Slice icon. Create two slices, one at one extreme of the box and one at the other.

• Select the Tong icon. With the mouse, click on the side of one slice, release the mouse, and while holding the shift key down click and release on the other slice with the tool.

• Choose "Save Image Sequence" in the File menu. When this is chosen, pick the Space option. A dialog box will appear, and depending upon the incremental detail desired between the two slices created, a large or small number of equally spaced frames may be generated between them.

• The generated pictures will be saved in a format accessible by a program named Projectionist. Projectionist is activated by triggering the created file once out of the Dicer program. What will be seen is a sequential presentation of the frames. The speed of the sequence may be increased or decreased.

Appendix 3 - Use of Workbench Mac

The data acquisition board was purchased from Strawberry Tree, Inc. Workbench Mac is the software they provide to support their data acquisition boards. Although simple to use, it is not extremely robust or versatile. Fortunately, it accomplishes the necessary tasks for this project. The following discussion will describe the basic use of Workbench Mac as it pertains to the project.

When Workbench Mac is activated there is a menu at the top of the screen, and there are a variety of boxes or icons on the workspace itself. If the icons are not shown when the well measurement program is run, they can be shown by choosing the Show Worksheet command from the Windows menu. This will hide the meters and charts and show the icons which provide the instructions for the logging of the temperature versus depth data. Figure 9 shows a Workbench Mac schematic for one logger.

The boxes with the simple math symbols on them are calculation icons and operate mathematical functions on one or two input values, and they provide a single value output. The calculation of temperature from the analog input of the thermocouple transmitter requires the use of three calculation icons. It is a more complex task to calculate the depth at any given time. After calculation of these two parameters, they can presented on the screen using the meter icons or the chart icons. The log-to-disk icon is used to store data to a file. Logging data may be begun or halted from the Start (Stop) all logs command in the Log menu at the top of the screen.

The temperature data from the thermocouple transmitter is received on an analog input channel at the data acquisition board. The analog input icon represents the data entering from this channel. It seems best that each channel is religiously assigned to a single well for the duration of the project (i.e. Channel 1 corresponds to TEP-001...). The analog input channel is set to a range of a 20 mamp signal across a precision 25 ohm resistor. The "Low noise (17 msec)" @ 10 hz sampling rate is chosen.

The data from the analog input icon then passes through a calculation icon to linearize the signal between 0 and 150 for signals between 4 and 20 mAmp. The signal then passes through a calculation icon which has a parabolic equation with coefficients determined from the calibration procedure. The coefficients are input for the logger number at any given well number. It is important to remember that the two numbers may not be same. The final calculation icon to determine the temperature at a well averages the data every 1 sec to provide an increase in signal stability. This averaging time is equivalent to averaging over a 4 in interval due to the probe lowering rate of the loggers.

The calculation of depth is determined using the signal from an encoding wheel. This allows for at least a precision to within one rotation of this wheel. For greater precision in between rotations, the velocity of the previous rotation is calculated assuming a minimal change in velocity from one period to the next. To infer the additional depth since the last rotation of the encoding wheel, the time since the last rotation is multiplied by the last calculated velocity.

The depth data from the encoding wheel is received on a digital input channel in the data acquisition board. The digital input icon represents the data entering from this channel. As with the temperature data, the digital channel number should correspond to the same well number. Sampling rates for these channels should also be set to 10 Hz. The data that leaves this icon is either 1 or 0. When the reed switch at the encoding wheel is close to the magnet on the encoding wheel, the switch triggers the input module at the data acquisition board. This can be seen at the board when the LED light near the input module goes on. When the reed switch is in the untriggered state, Workbench Mac interprets this as a 1. When the switch closes, it interprets a 0.

The data from this channel goes into a pulse icon. The reason this icon is used is to compensate for the fact that it will never be sure exactly how long the magnet on the encoder wheel will be in the vicinity of the reed switch. This icon assumes the switch is closed for less than a specified time, .5 sec, and later this time is added to the total time used for one encoding wheel rotation. This icon goes to the opposite of its start value when the value into it is less than or equal to zero. When the signal is greater than 0 it starts at the start value, and then goes from high (1) to low (0) for the durations specified. The start value is low for the specified .5 sec, and high for some long period greater than one full encoding wheel rotation, say 3600 sec. The start value is designed to be low because a timer icon which this is connected to begins timing once it goes high. The timer icon remains at it last value when the signal attached to it is low and resets to 0 when it the signal becomes high. So, the timer records the time since the last closing of the reed switch minus the .5 sec. The value of this timer will be referred to as the "current time".

The current time is sent to two calculation icons. One icon is used to calculate the current additional depth since the last pulse. The other records the time for one complete rotation to calculate the wheel velocity for the next encoding wheel rotation. The velocity calculation is achieved by sending the current time to a calculation icon which stores the maximum time it has seen for 1 sec. The choice of 1 sec was arbitrary. It was chosen to be long enough so that the maximum time is not lost when the timer is reset by the pulse (i.e. greater than the pulse low signal duration) and short enough that it is not possible that another complete rotation might occur.

The value from this calculation icon is sent to another calculation icon which stores this value until it is reset to store another. The way the memory function in this calculation icon is reset is when a value greater than 0 is sent to the other available input value of the calculation icon. Recall that the pulse icon is designed to give a low signal when the encoding wheel completes a rotation. To store the most recent time elapsed to complete a rotation, the beginning of a new wheel rotation needs to reset the memory icon. To achieve this with the pulse function, the low signal and high signal values need to be reversed, so a calculation icon changes the low pulse signal to 1 and the high pulse signal to 0. This then is routed to the memory calculation icon to reset it.

Both the current time and past rotation time values are sent to the same calculation icon where the ratio of the true current time and the true past rotation time are calculated and multiplied by the encoding wheel circumference. This gives the current depth lowered since the last rotation. The current time is not the true current time because it is .5 sec less due to the pulse icon. The past rotation time is similarly off by .5 sec. An additional .5 sec is added to both of these values in the calculation icon before their ratio is taken. In the same icon the ratio is multiplied by the encoding wheel circumference. The value of this icon will be referred to as the "current depth". It is possible for the current depth calculation to be less precise than expected due to possible variations in the lowering speed resulting from the probe getting temporarily caught on the way down. To limit this error, the current depth is sent to a calculation icon which has a clip function. This limits the current depth to a value no greater than the circumference of the encoder wheel.

To obtain the total depth, the current depth is added to the depth up to the last rotation. The last rotation depth is gained by a calculation icon which sums the pulse total. This icon is attached to the pulse icon and counts the number of times that the pulse goes high. It can be reset by a value greater than 0 attached to its other available input value. A reset button which is a calculation icon that goes high as long as it is pressed is attached to the pulse counter. This is used at the beginning of a monitoring operation to reset the depth. The rotation count is sent to a calculation icon where it is multiplied by the encoder wheel circumference. The current depth is added to this in the same icon to achieve the total depth.

Another value is added within this final calculation icon which compensates for the initial offset of the probe from the surface. There is no simple method to provide an initial velocity of the wheel, so the depth calculation will be incorrect until the first rotation of the encoder wheel has occurred. Before the magnet attached to the encoding wheel passes by the reed switch, the program indicates a depth equal to the initial offset value plus one full rotation of the encoding wheel. Therefore, the initial offset value should be the initial depth minus the circumference of the encoding wheel. The initial depth value should be positive for probes with a starting point below the surface because the depth is calculated as a positive value. For this offset to be accurate, the probe must be in the same initial position before each logging session. So that the velocity after the first rotation is as accurate as possible, it is recommended that the initial encoding wheel position is such that the magnet has just passed beneath the reed switch once the probe begins its descent.

Appendix 4 - Operational Monitoring Procedure

• Take the cover off of the well. Remove the well cap. Remove the cover from logger.

• Center the probe port at the base of the logger over the well.

• Plug the unit in.

• Place the thermocouple wire on the encoder wheel. Insure that the thermocouple wire is properly spooled around the bicycle wheel. A nasty rat's nest of wire can result if the wire falls off the rim. If slack is needed, press the down button for as long as needed. Since the remote switching connections are not yet attached, the device will stop moving down once the button is released.

• Unwrap the two pieces of duct tape wrapped around the rim which insure the wire does not unwind from the rim. A neater method for the future might be some velcro.

• With the use of the up and down buttons, position the sinker attached on the probe end of the thermocouple wire 1 in to the left (when facing the switch panel) of the switch located at the encoder wheel.

• Rotate encoder wheel so that a preplaced mark on the wheel is in line with the switch. An accurate depth calculation is insured with the probe and the encoder wheel in the same position before each monitoring operation. The mark on the wheel creates a repeatable condition. The initial offset depth of probe from the ground surface can be changed within the Workbench Mac program designed for this project.

• Insure that the wells to be monitored are plugged into the patch board. This patch board is installed to prevent wires crossing the site boundaries during electric heating.

• Cover the logger to prevent ambient temperature fluctuations (especially on windy days) from effecting the cold junction compensation at the thermocouple transmitter. It requires some care to insure that the hinged plexiglass protective cover does not dig into the cables.

• Attach both the data connection (right side of switch panel) and remote switching connection (left side of switch panel) plugs to each logger.

• Return to the computer. Activate the Workbench Mac program. If all the charts and meters are not shown, choose "Show worksheet" in the Layout menu. Insure all the wells to be logged are showing a reasonable temperature signal. The most frequent cause of a signal not displayed is that a logger is unplugged from its power source, or all cable connections have not be made correctly.

• Make sure that the remote switching box has been set to trigger only those wells which are set to log. Switch these to "Active" and the rest to "Inactive".
• Choose the Hide worksheet command from the Window menu. Double-click on the disk icon at the far right of the Workbench Mac program. Select "Save as", and choose the name and location to save the data file to. Select Show worksheet from the Window menu.
• Press the "down" button on the remote switching box. This will allow the lead sinkers to pass beneath the switch at the encoder wheel.
• Click on the Manual Reset buttons of the program long enough for the depths to reset. One is for wells 1-6 and the other is for wells 7-12.
• Select "Start all logs" in the Log menu. There may be times when one will forget this step. If one activates the loggers and forgets this step, press "Off", then press "Up", wait a long enough period of time for the lead sinkers to pass beneath the switch again. Then begin from this point again. Be absolutely sure the "Up" switch is never pushed once the lead sinker has passed beneath the switch at the encoding wheels. If this were to happen, there would only be the safety tension switch to prevent the probe or logger from damage.
• Press the "down" button again.
• Check that the red LED's on the data acquisition board are lighting up periodically (about once every 4 seconds) to indicate the encoding wheels are rotating. This can also be seen on the depth calculations of Workbench Mac as monotonically increasing functions. If one stays a at a particular depth, this is an indication that one has stopped lowering.

If a logger stops lowering or turns off for no apparent reason, this is an indication that the probe got caught in the well and is still lodged or loosened up and then began to lower abruptly. A repair which works many times is to file a small amount of metal off of the reflector end. Round any exposed edges on the reflector, probe holder or on the teflon fork where the probe is connected to the thermocouple wire. Another reason for the probe to stop lowering is that the weld where the rim is put together can sometimes catch the thermocouple wire. This can be fixed by grinding this weld smooth.

If a signal takes an abrupt jump (notably downwards), this is a possible indication that condensation formed on the sensor and prevented a proper infrared reading. Further indications of this is that the temperature slowly begins to rise, or when it is raised to the surface the temperature does not change. This problem may be cured in two ways: get rid of any excess moisture that has collected at the base of the well, or if it is a cold day, let the probe rest at about a 30 ft depth until it equilibrates with this warmer temperature.

• After approximately 10 minutes, all the wells should be logged?!

• Disconnect the patch board.

• Rewrap the duct tape around the rim to prevent the thermocouple wire from unspooling. Place the probe in the box. Unplug the logger from the electrical and signal connections before covering the logger. Replace the logger cover. Cap and cover the well.

There are a few additional future steps that should be considered to provide a more efficient monitoring system. The top of the box could be cut off and reattached with hinges on one side. This will facilitate the current hindrance in removing a replacing the logger cover. Although it is not time consuming to remove and replace the well cap and cover, insert and remove the probe, the cumulative time for eleven wells is on the order of tens of minutes. An aluminum cover that fit over the Christy box hole with a small cylindrical rise (e.g. from a short pipe section screwed in) would allow the logger to be left in position.

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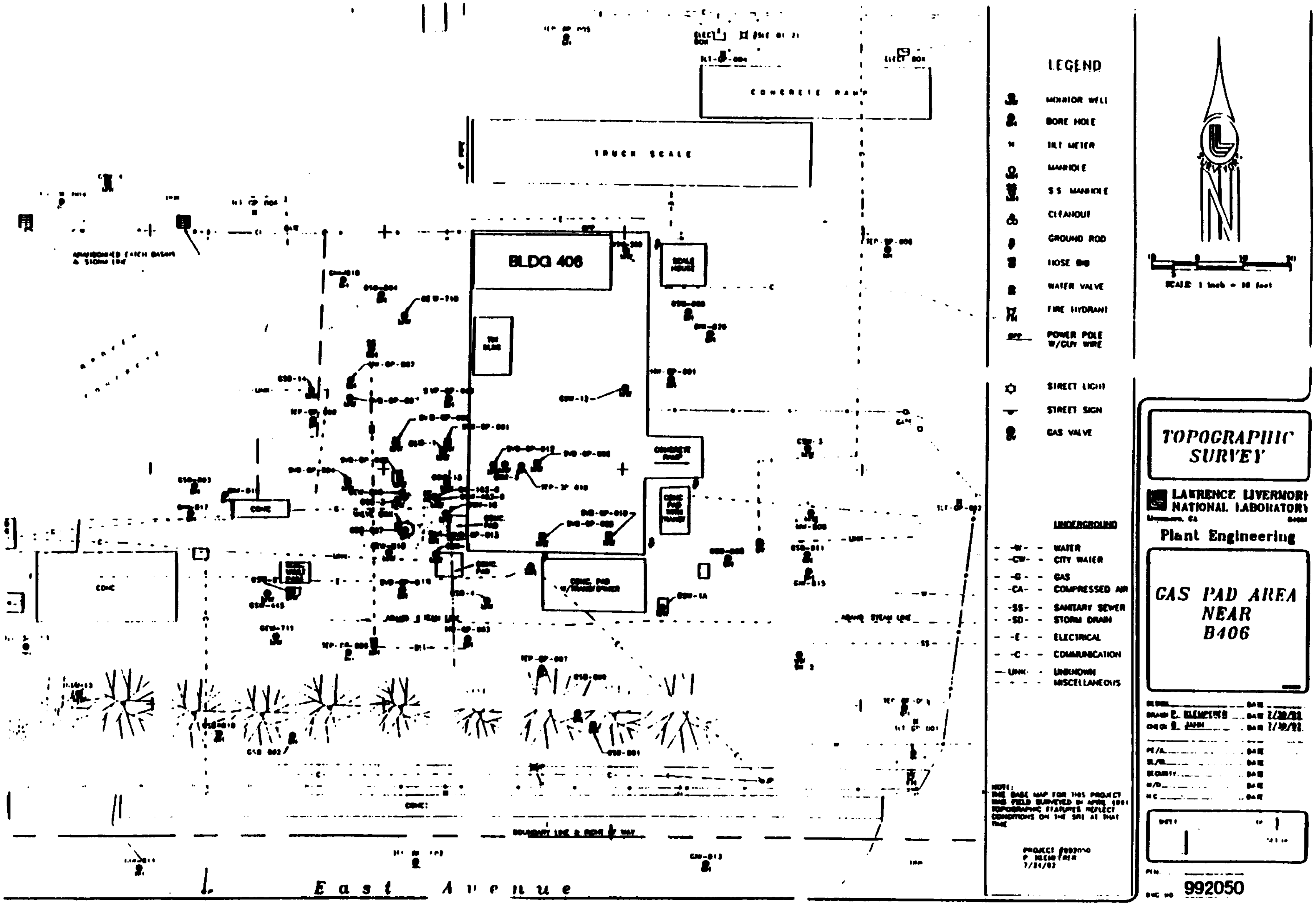

Figure 1 Site Layout

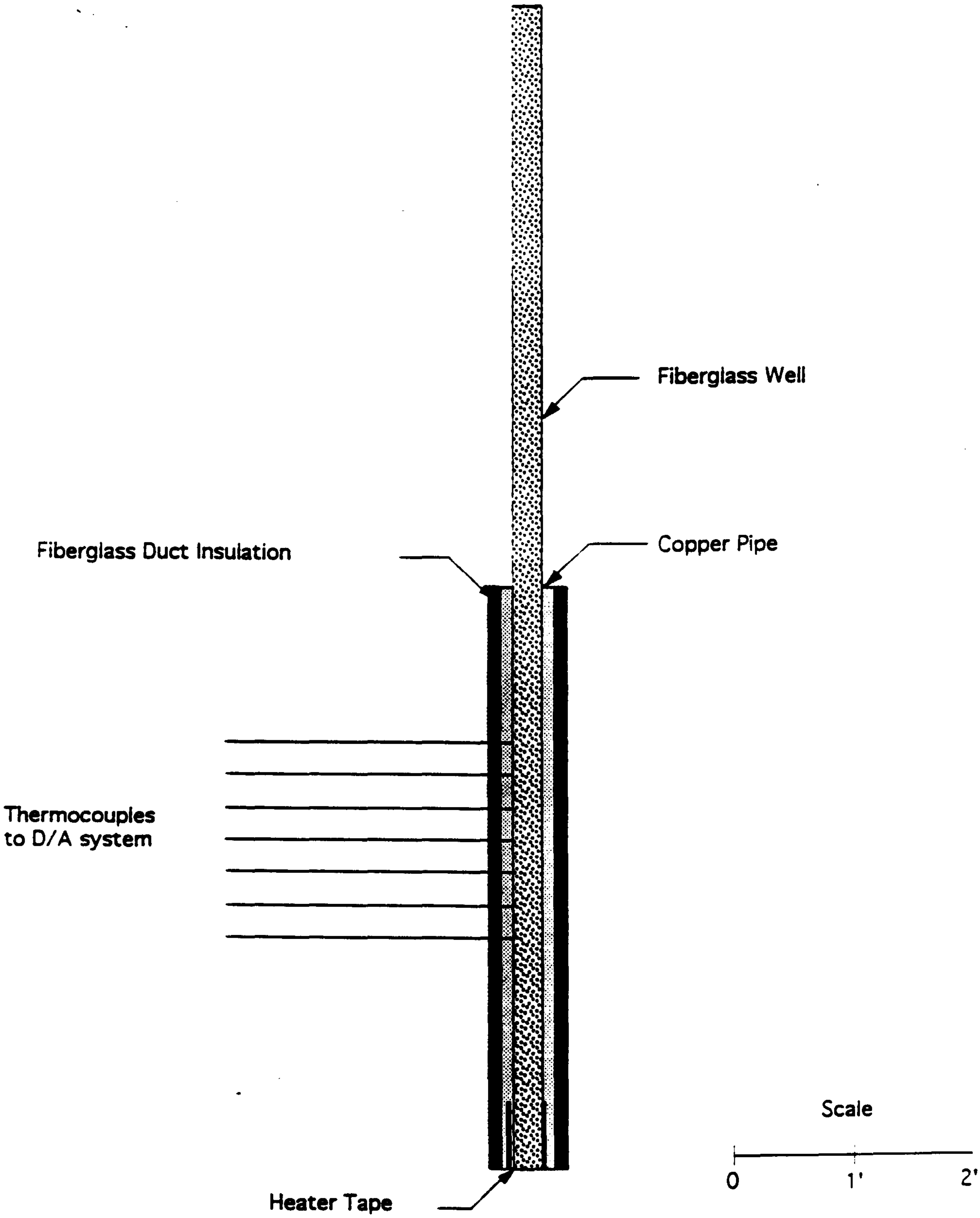

Figure 2 Schematic representation of experimental device used to quantify natural convection occurring in fiberglass well.

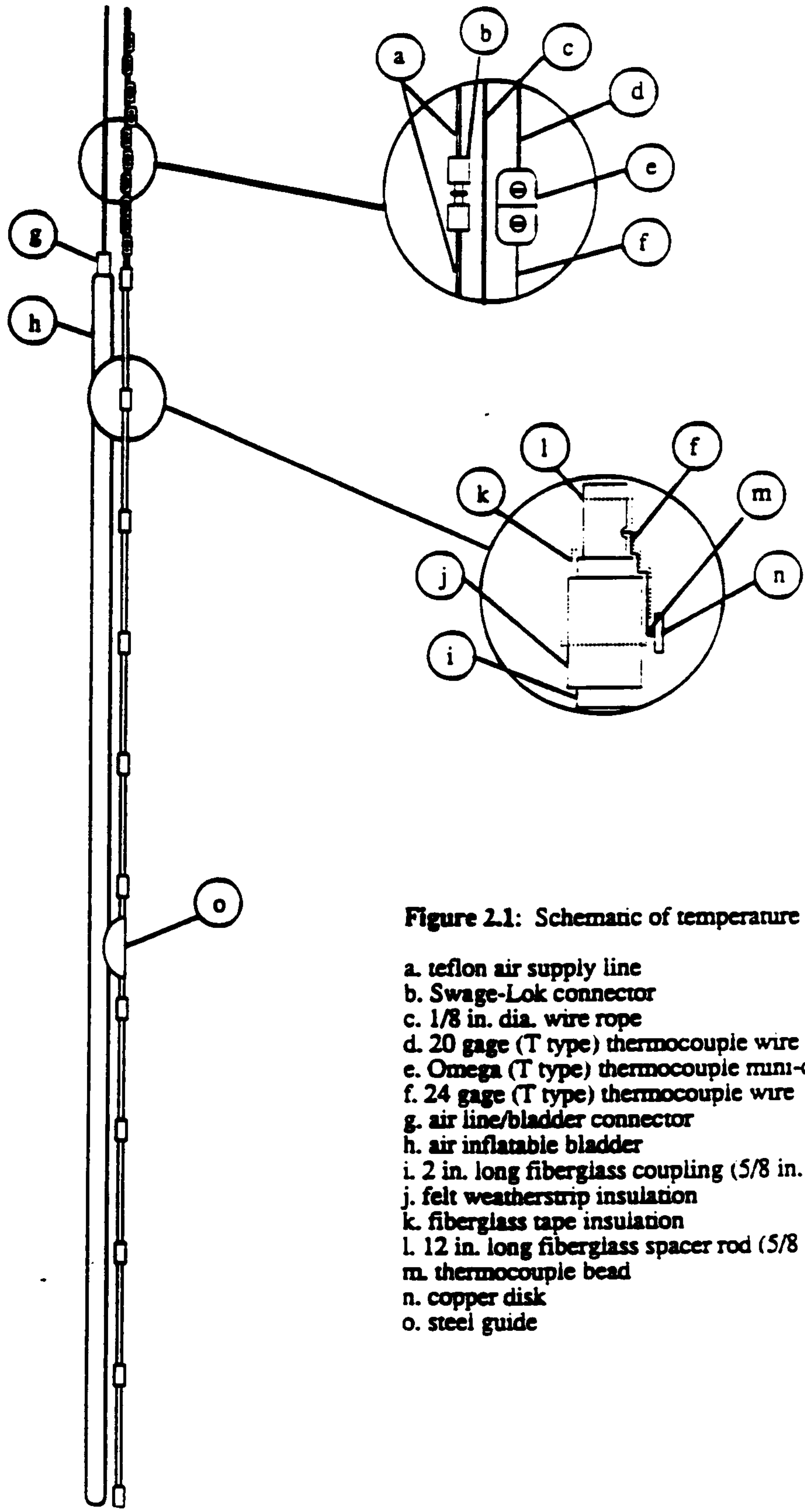

Figure 2.1: Schematic of temperature probe.

a. teflon air supply line
b. Swage-Lok connector
c. 1/8 in. dia. wire rope
d. 20 gage (T type) thermocouple wire
e. Omega (T type) thermocouple mini-connector
f. 24 gage (T type) thermocouple wire
g. air line/bladder connector
h. air inflatable bladder
i. 2 in. long fiberglass coupling (5/8 in. ID)
j. felt weatherstrip insulation
k. fiberglass tape insulation
l. 12 in. long fiberglass spacer rod (5/8 in. OD)
m. thermocouple bead
n. copper disk
o. steel guide

Figure 3 Original temperature measurement device used at clean site

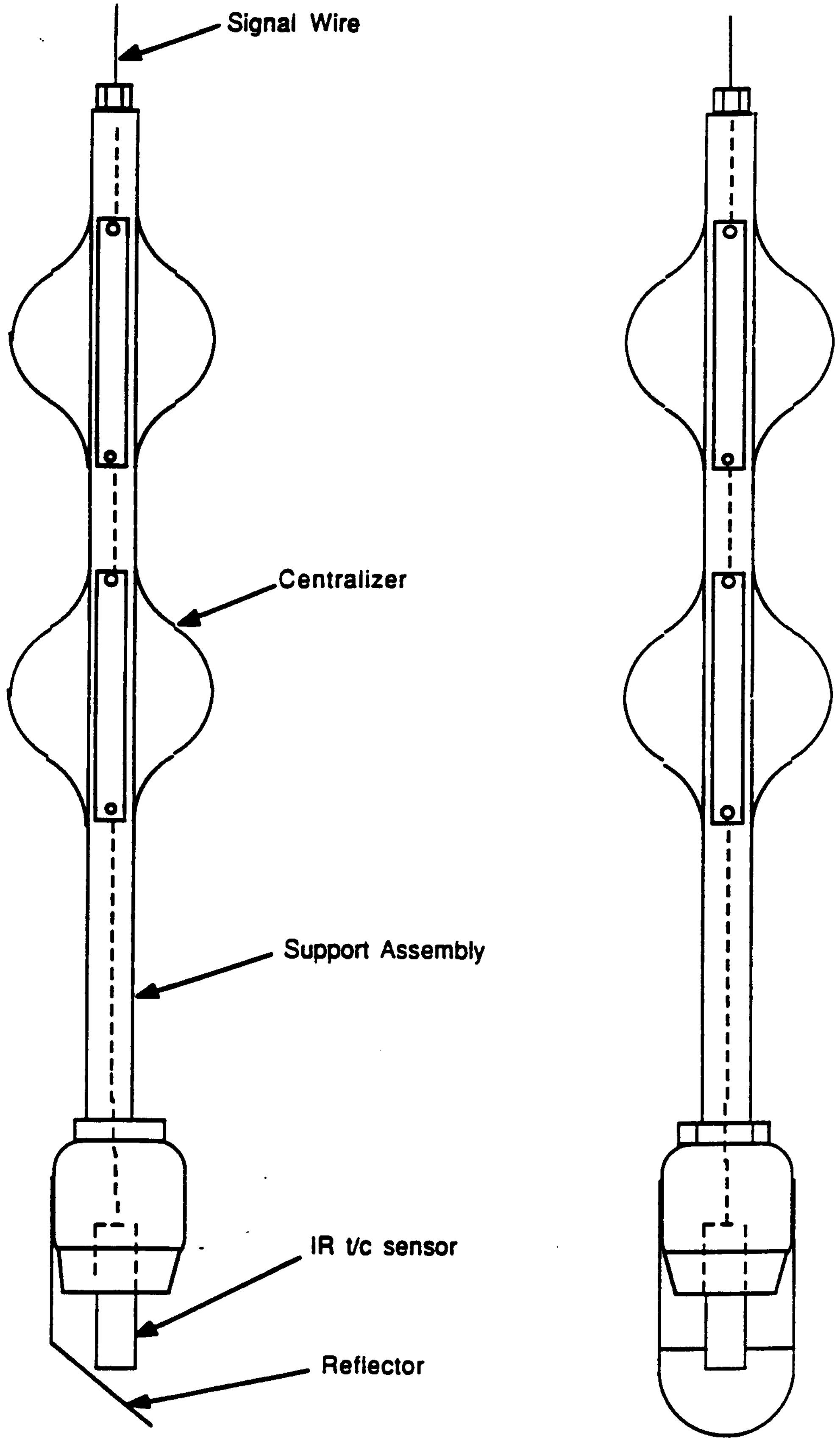

Figure 4 Infrared sensor mounting configuration for downhole temperature measurement

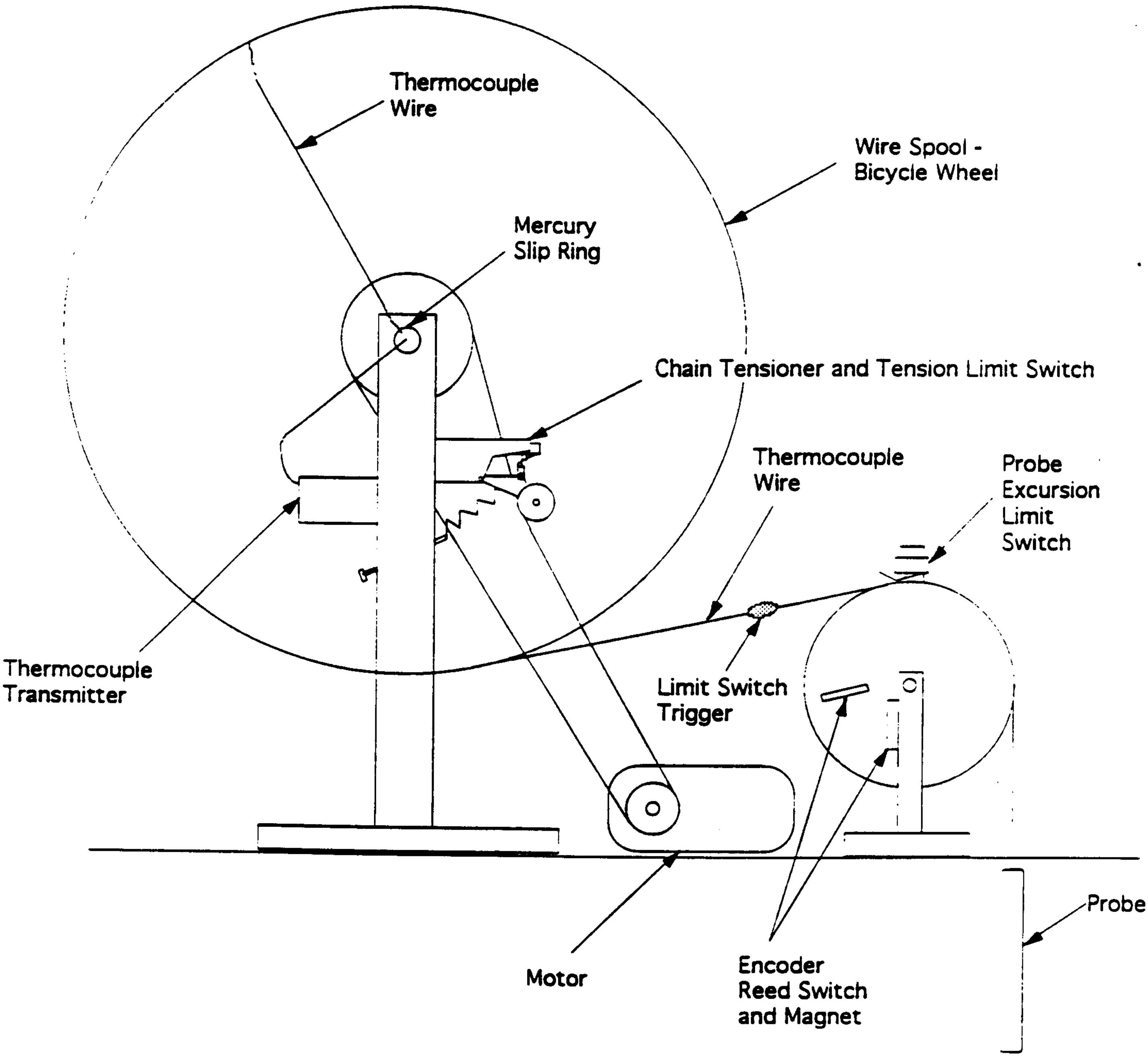

Figure 5 Schmatic of logger.

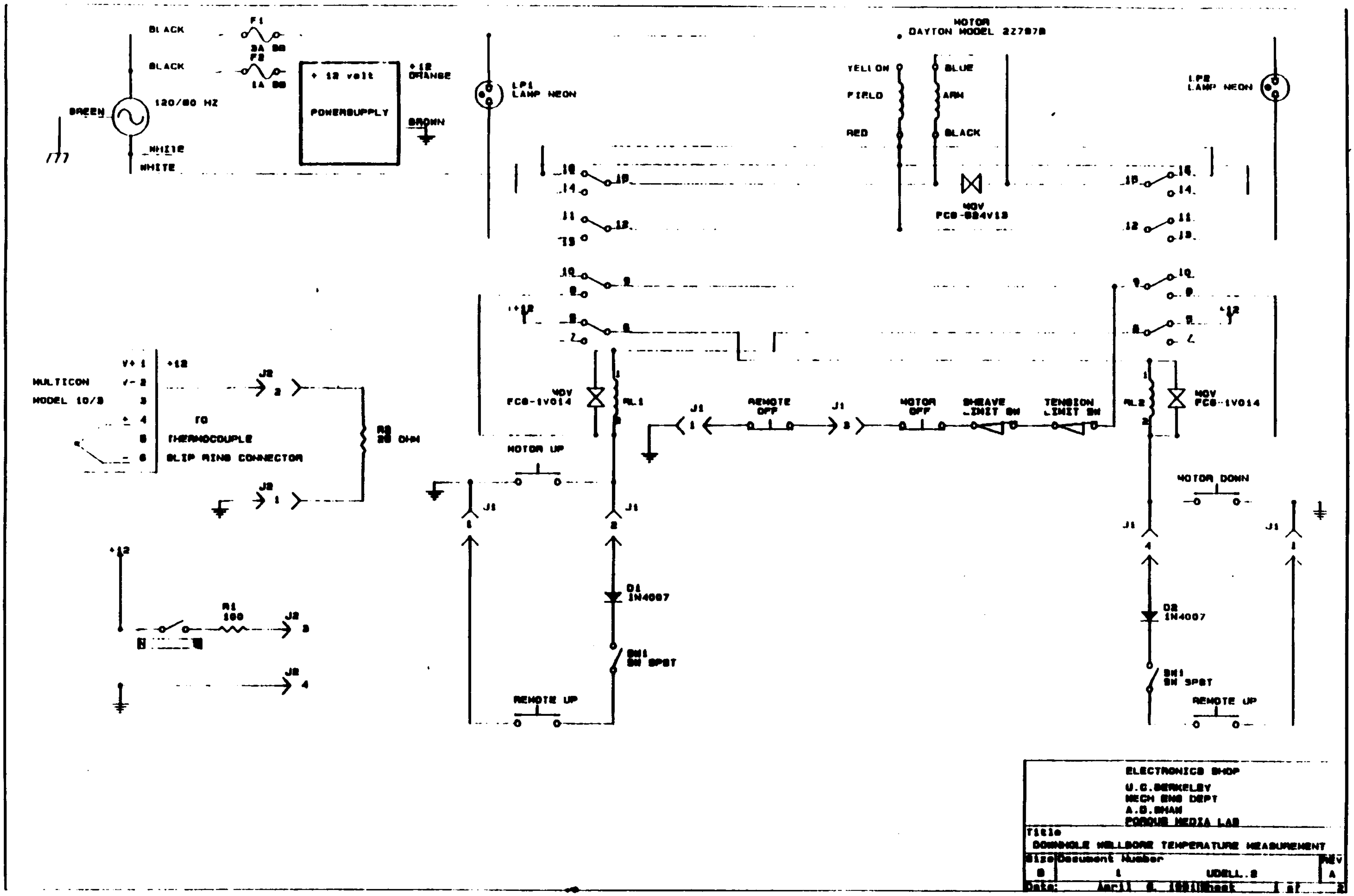

Figure 6 Logger electronics schematic

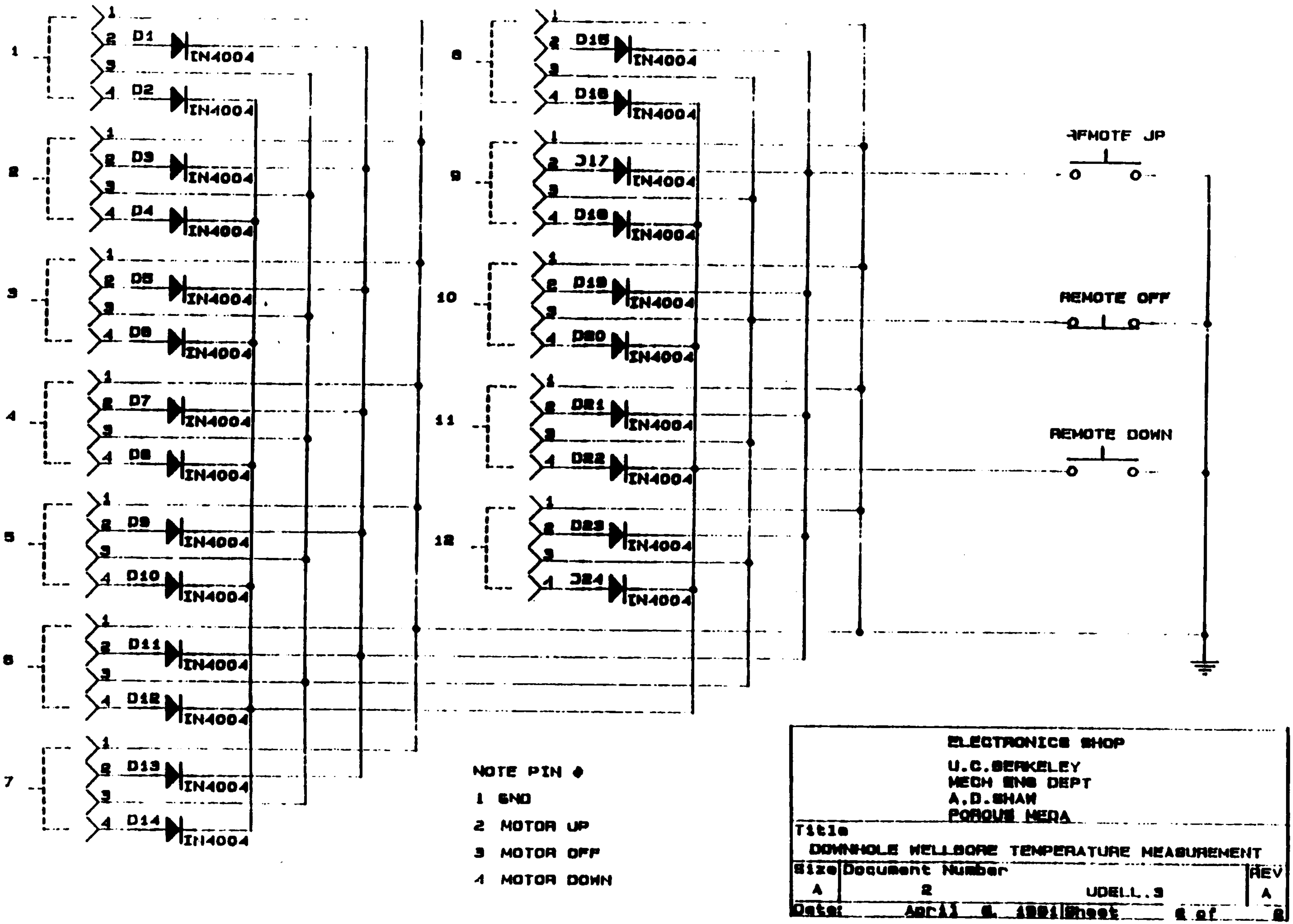

Figure 7 Switch box electronics schematic

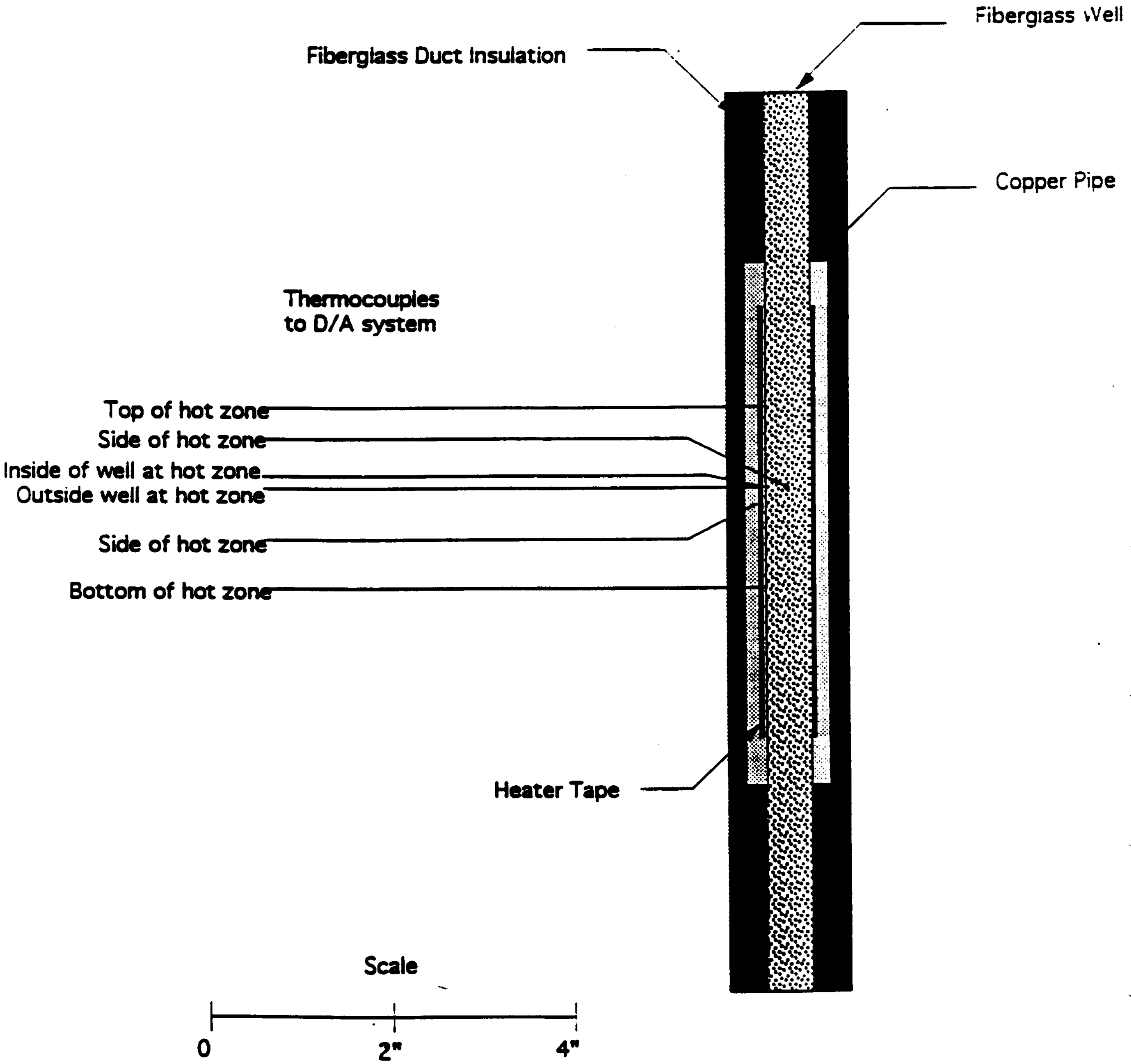

Figure 8 Schematic of fixture used to calibrate IR t/c sensor.

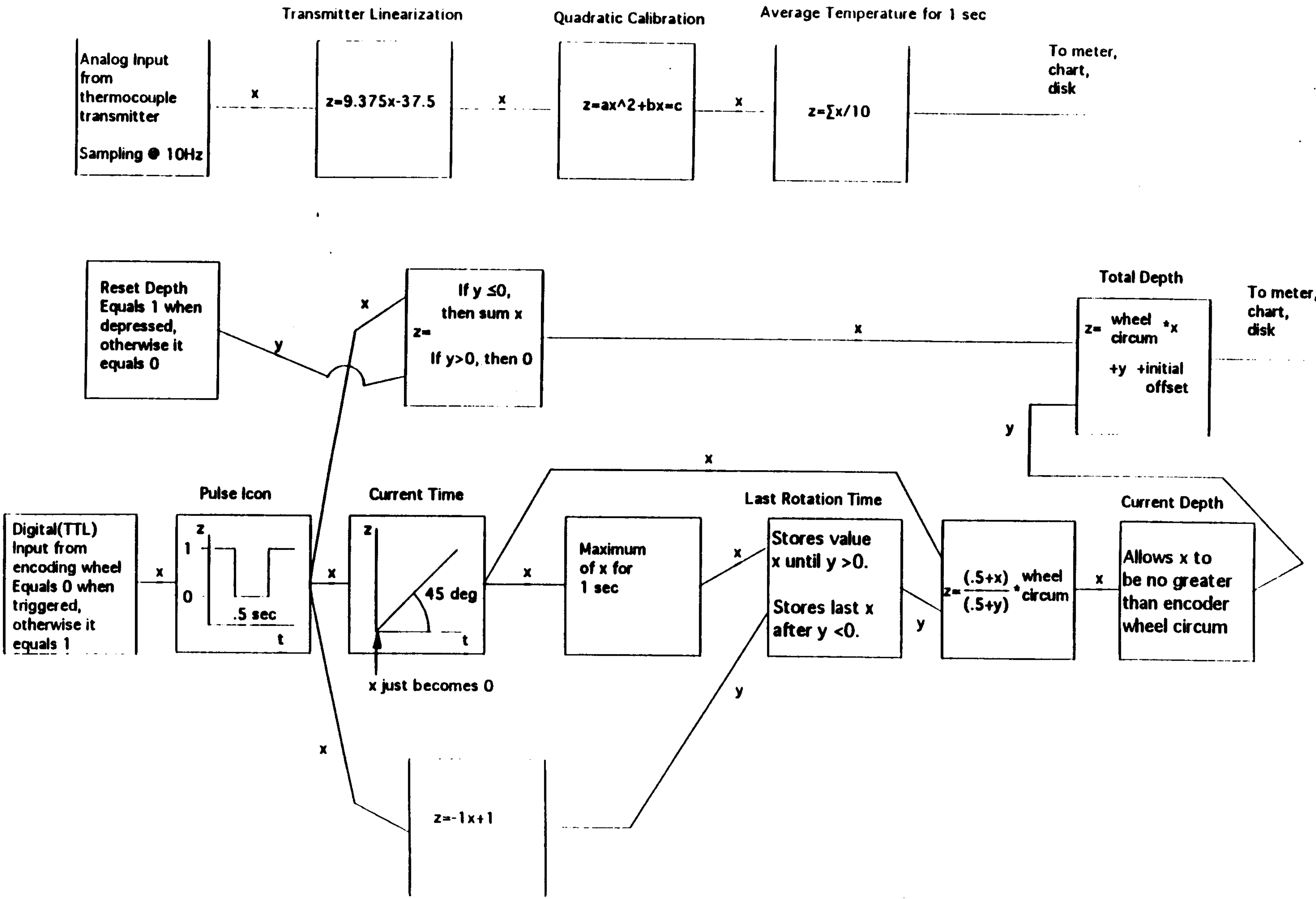

Figure 9 - Diagram of Workbench Mac calculations to obtain depth and temperature from logger signals

Table 1 Parabolic curve fit constant coefficients applied to 4-20 mamp linearization of thermocouple transmitter

Probe #	calibration date	curve fit constants to y = a + b x + c x^2 a	b	c
1	9/14/92	-12.03	1.24	-0.00221
2	9/16/92	-12.76	1.28	-0.00234
3	9/23/92	-12.99	1.298	-0.00232
4	9/24/92	-12.18	1.271	-0.00206
5	9/17/92	-12.21	1.203	-0.00176
6	9/10/92	-16.80	1.359	-0.00276
7	10/1/92	-12.92	1.265	-0.00215
8	9/21/92	-13.63	1.305	-0.00232
9	9/10/92	-20.38	1.468	-0.00336
10	9/15/92	-14.01	1.3	-0.00228
11	10/6/92	-13.25	1.28	-0.00228
Average *		-12.97	1.280	-0.00225
standard dev.		0.67	0.022	0.00010

hypothetical input value from linearized transmitter output	Corresponding output of parabolic curve applied to input from average of curve fit constants Avg	std. dev
20	11.7	1.4
25	17.6	1.2
30	23.4	1.0
35	29.1	0.9
40	34.6	0.8
45	40.1	0.8
50	45.4	0.8
55	50.6	0.9
60	55.7	0.9
65	60.7	1.0
70	65.6	1.0
75	70.4	1.1
80	75.1	1.2
85	79.6	1.2
90	84.0	1.3
95	88.4	1.3
100	92.6	1.4
105	96.7	1.4
110	100.7	1.5
115	104.5	1.6
120	108.3	1.6
125	111.9	1.7
130	115.5	1.9
135	118.9	2.0

* The average parabolic curve fit coefficients and standard deviations are with probe number's 5,6, and 9 excluded.
Earlier calibration procedures skewed the transmitter outputs.